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(54) **OPTICAL COMMUNICATION SYSTEMS AND METHODS**

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See application file for complete search history.

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Primary Examiner — Hibret Woldekidan

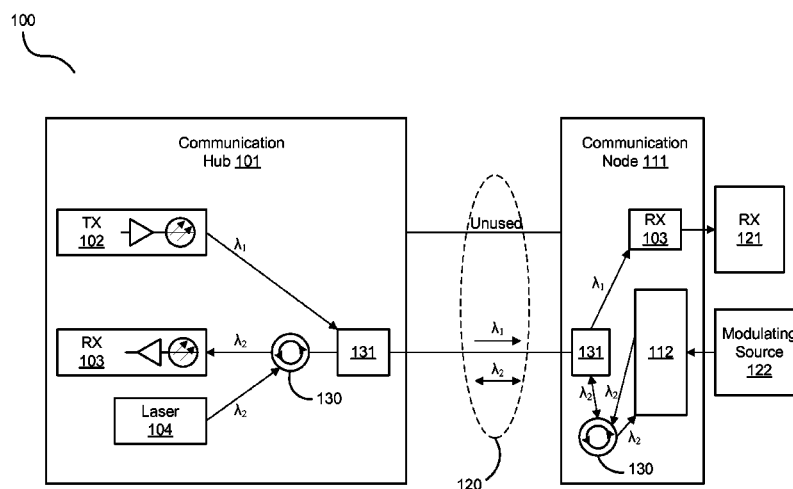
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(57)

**ABSTRACT**

Systems and methods presented herein provide for optical communications with a remotely located laser. In one embodiment, a communication system includes an optical link and a communication hub comprising at least two lasers optically coupled to a first end of the optical link, the communication hub further comprising an optical multiplexer operable to multiplex light from the lasers and to propagate the multiplexed light along the optical link. The communication system also includes a communication node comprising an optical modulator optically coupled to a second end of the optical link, wherein the optical modulator is operable to modulate the multiplexed light from the communication hub with one or more modulating signals, and to propagate the modulated light to the communication hub.

**20 Claims, 13 Drawing Sheets**



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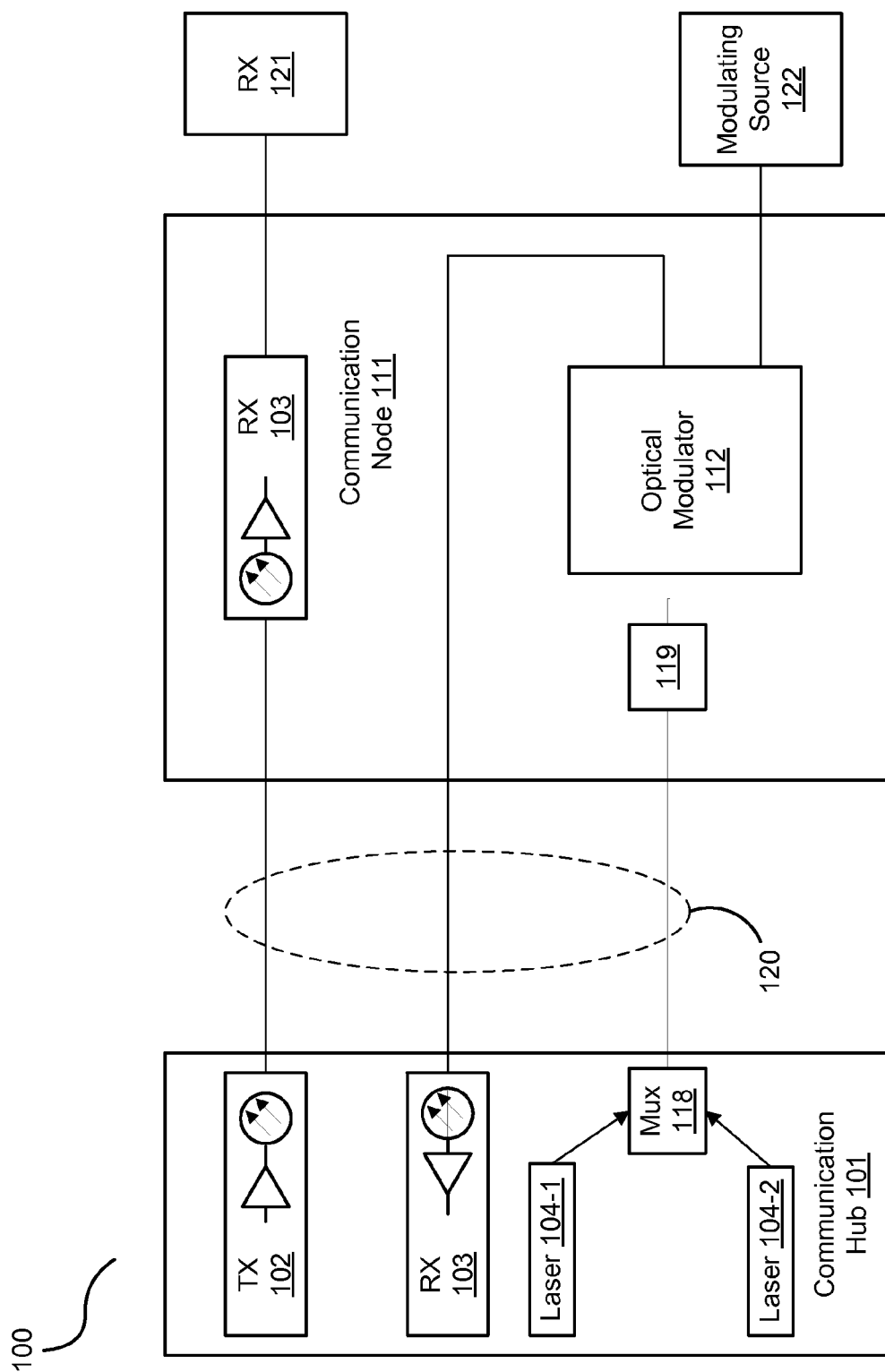
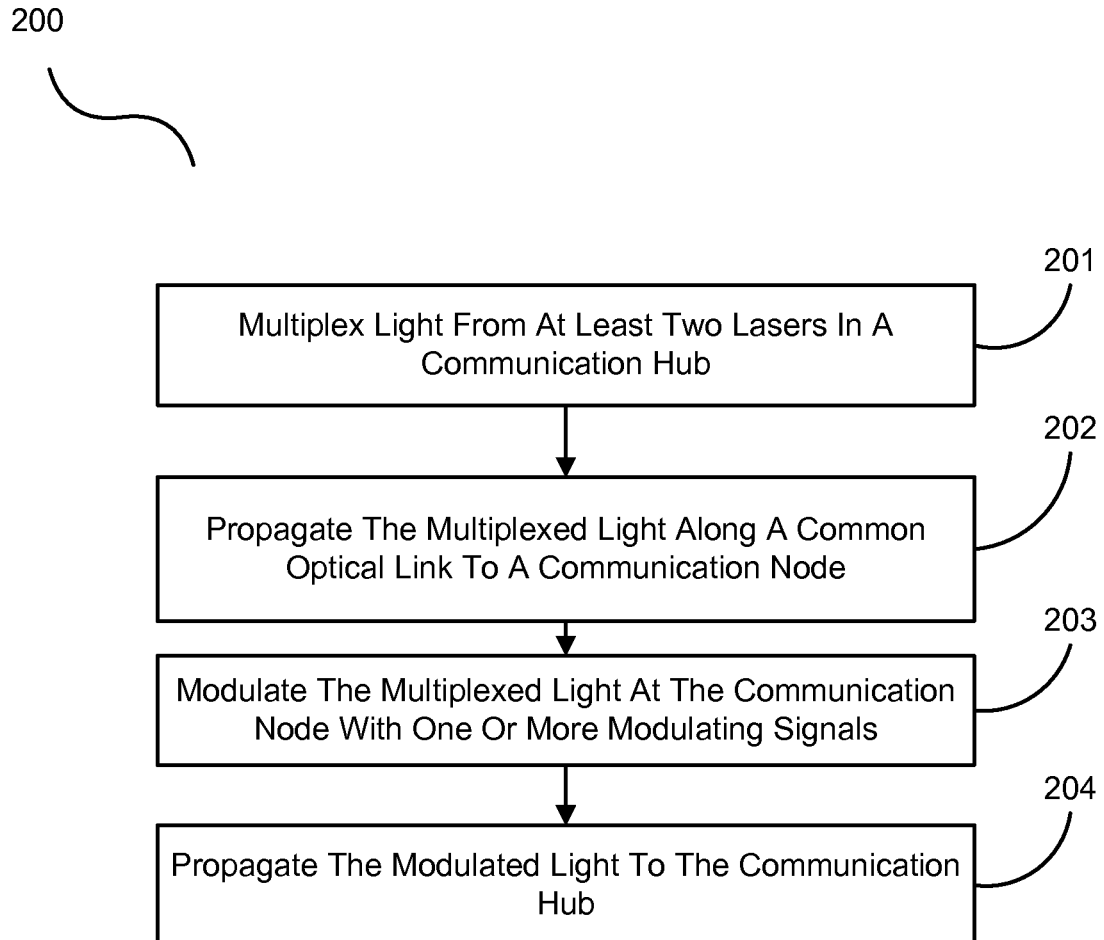


FIG. 1

**FIG. 2**

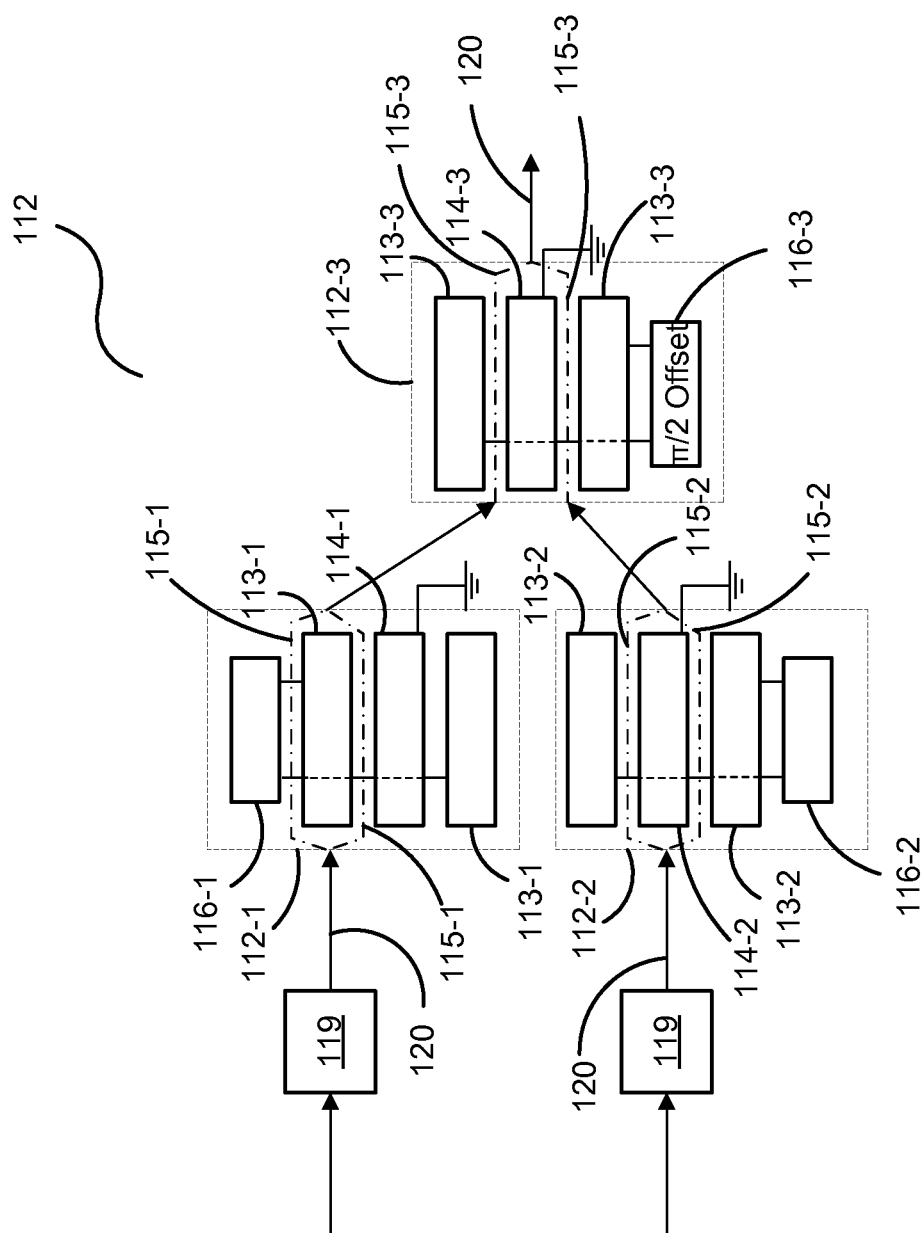


FIG. 3

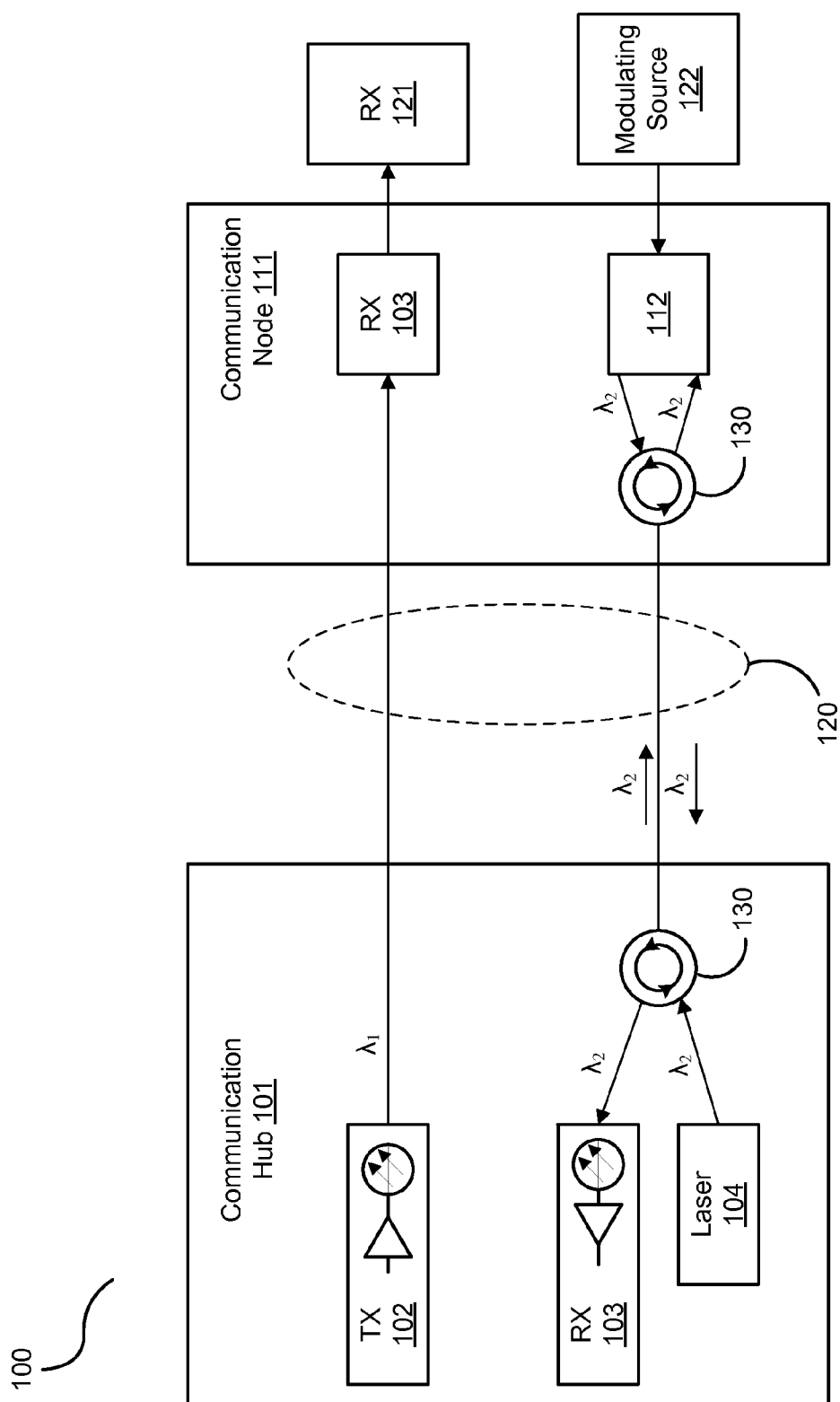


FIG. 4

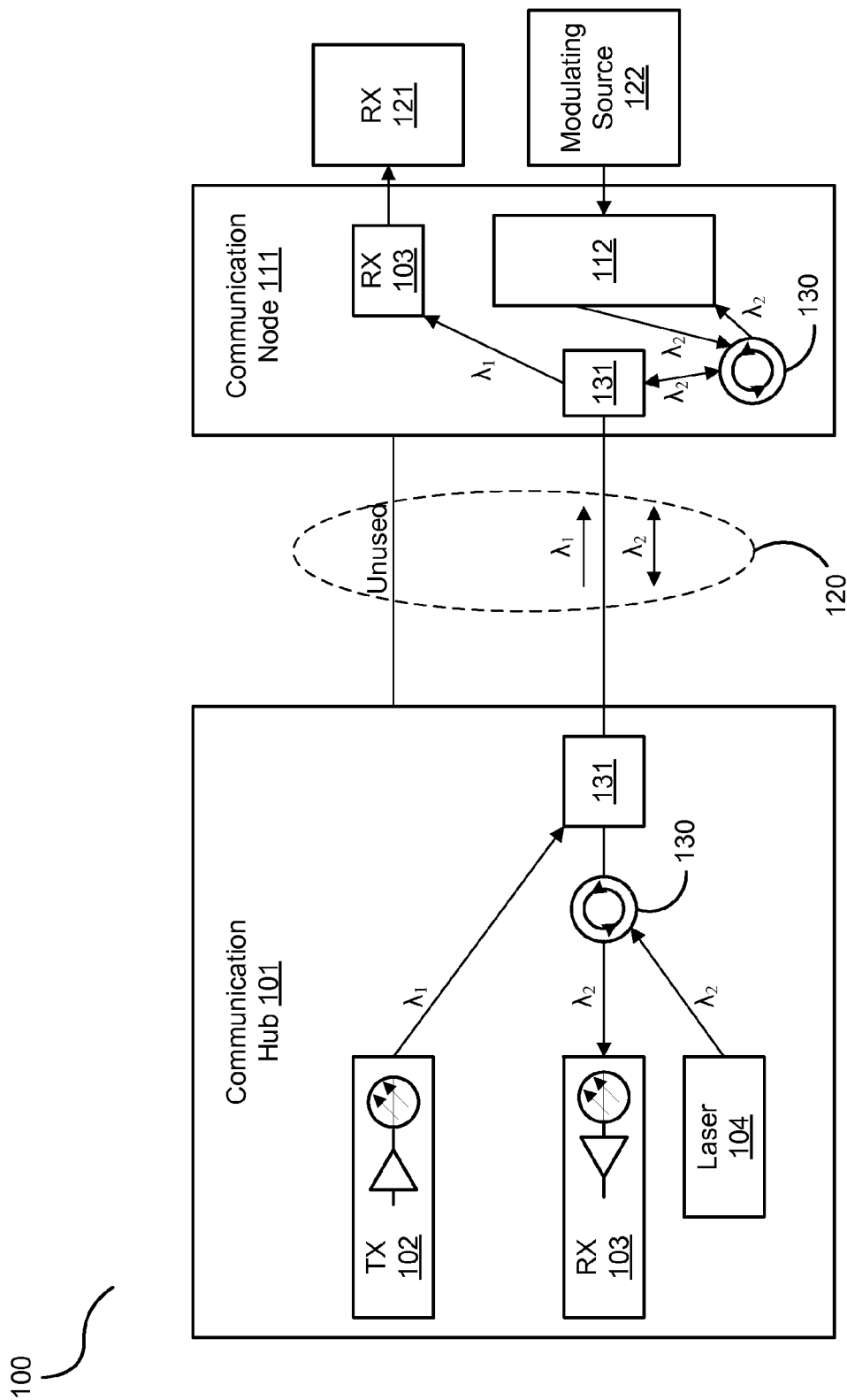


FIG. 5

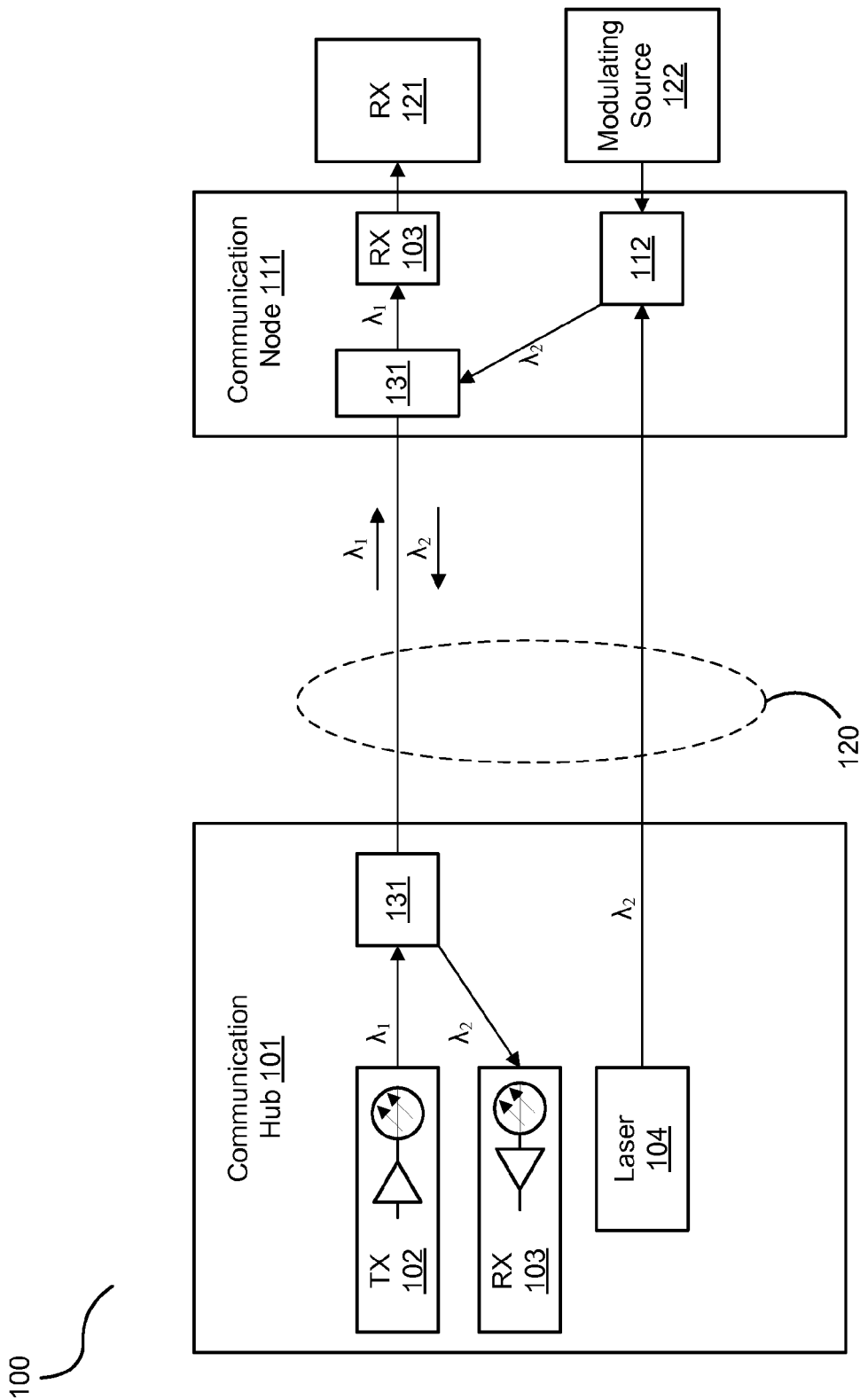


FIG. 6



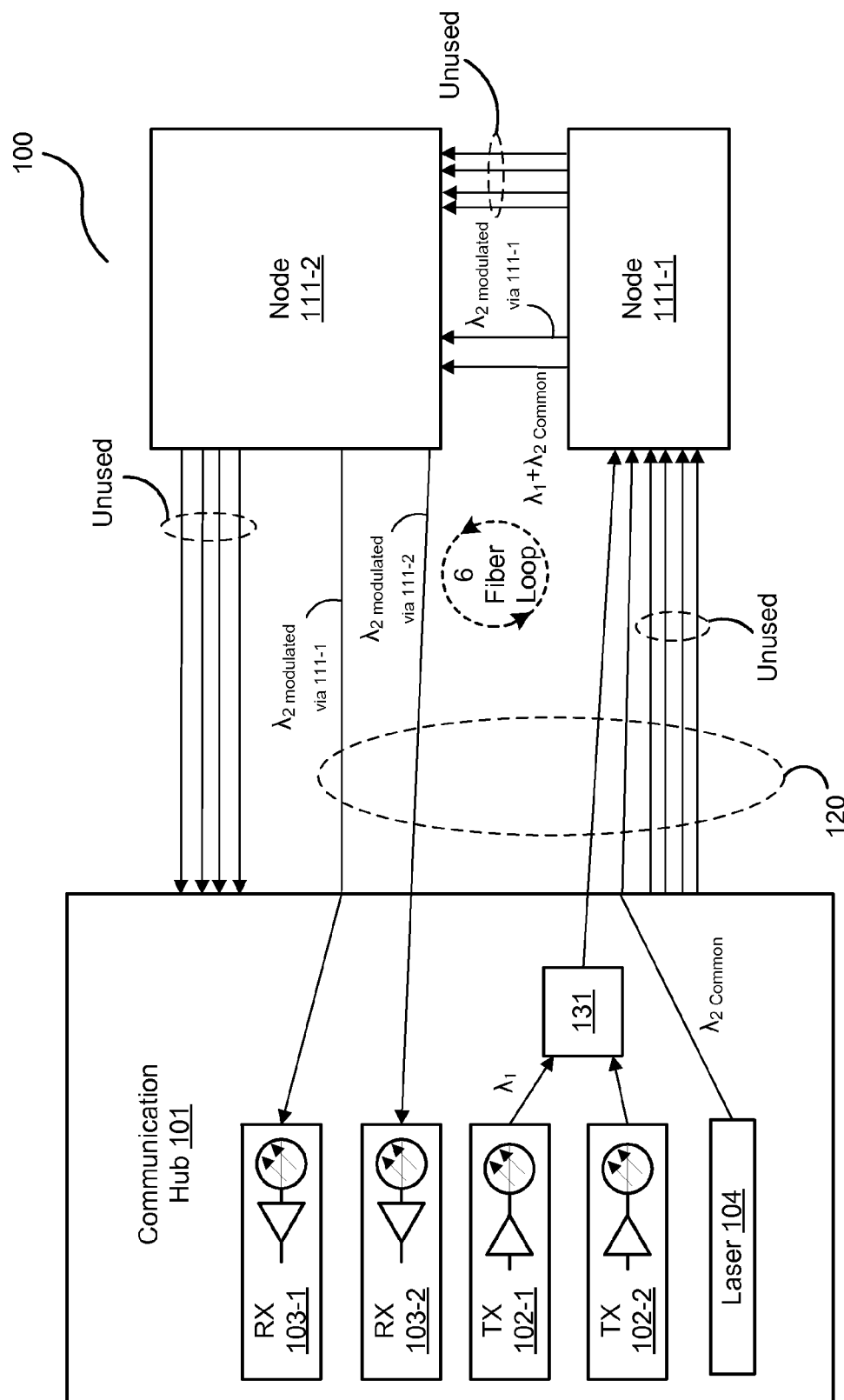


FIG. 7

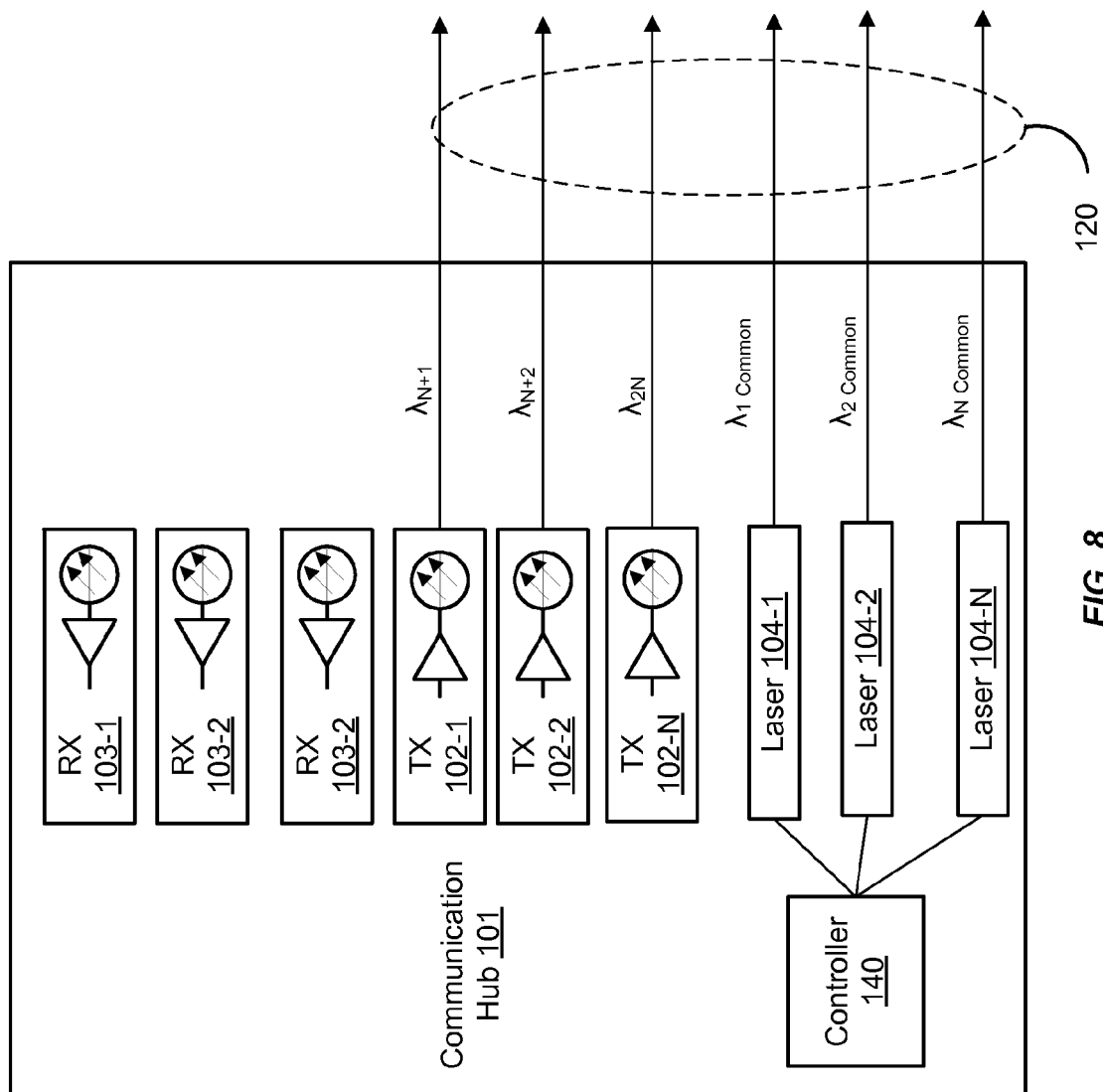
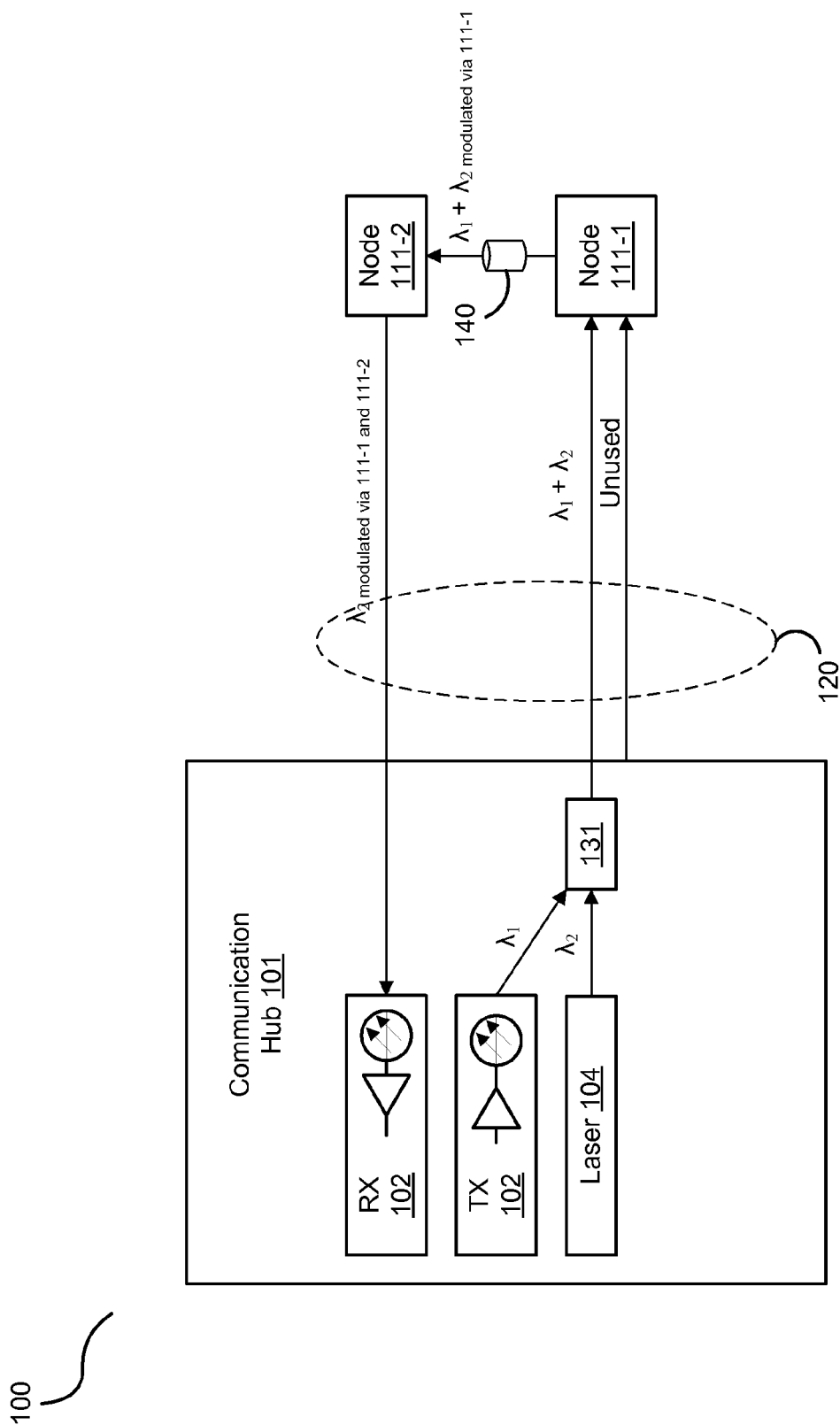


FIG. 8



**FIG. 9**

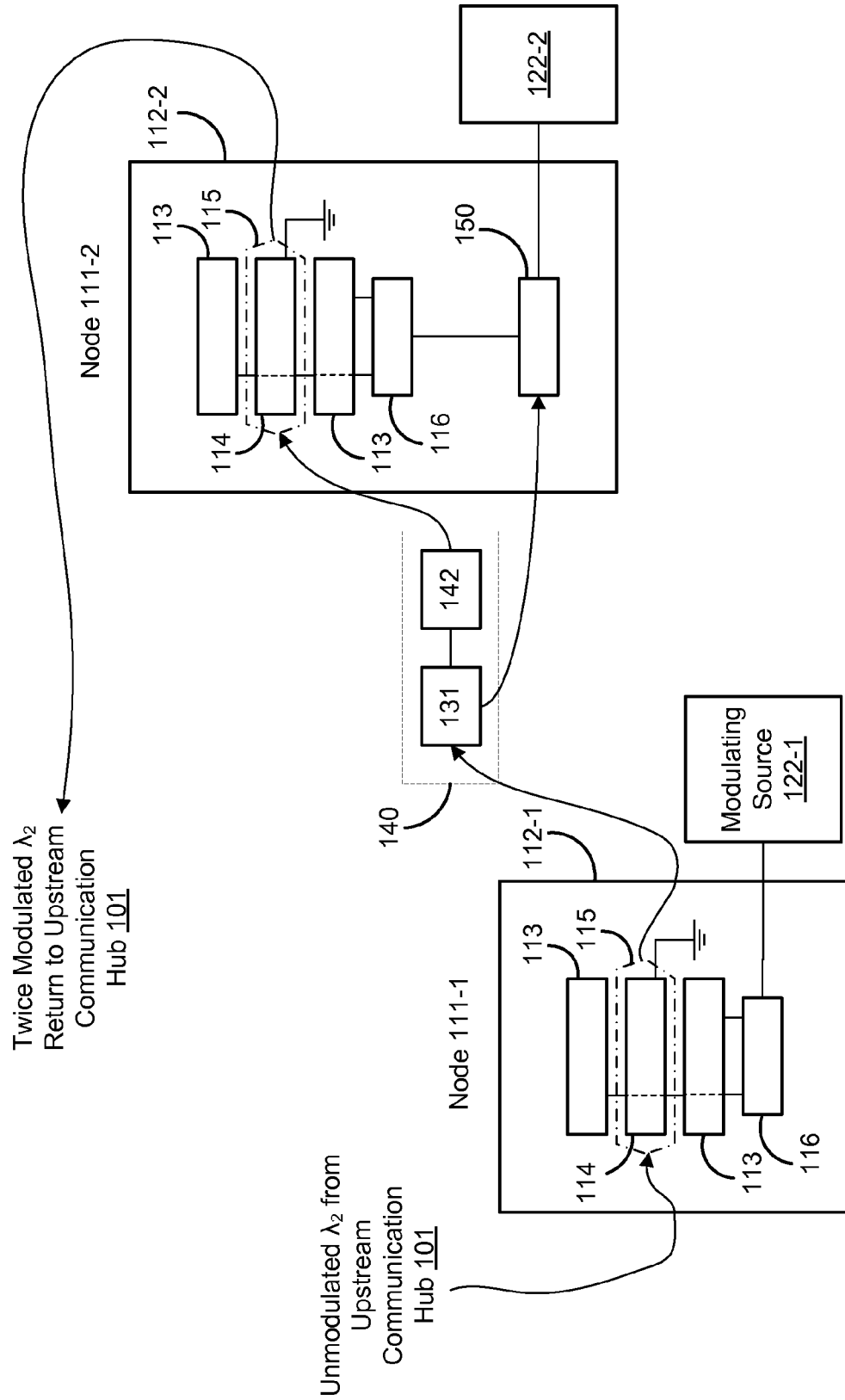


FIG. 10

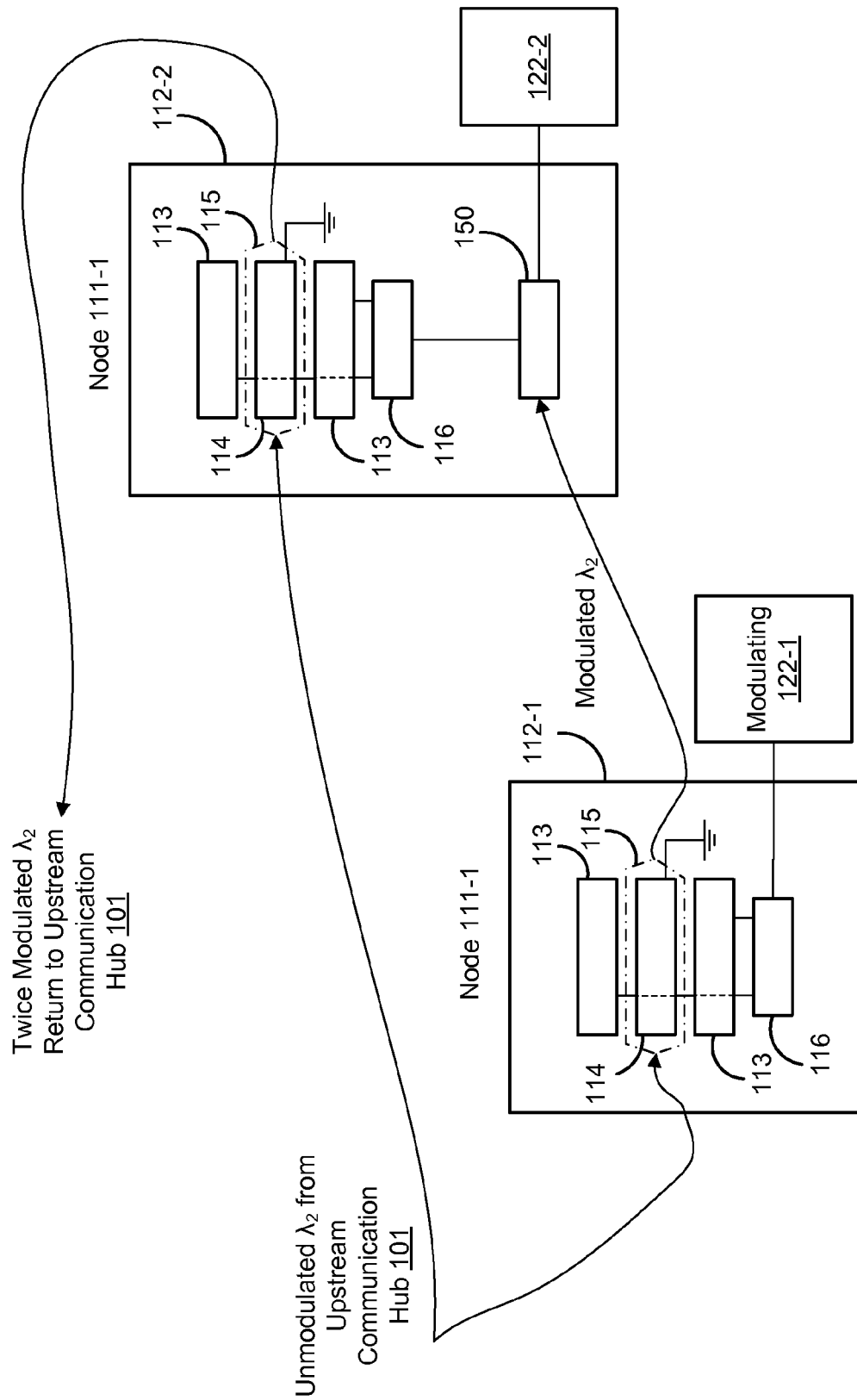


FIG. 11

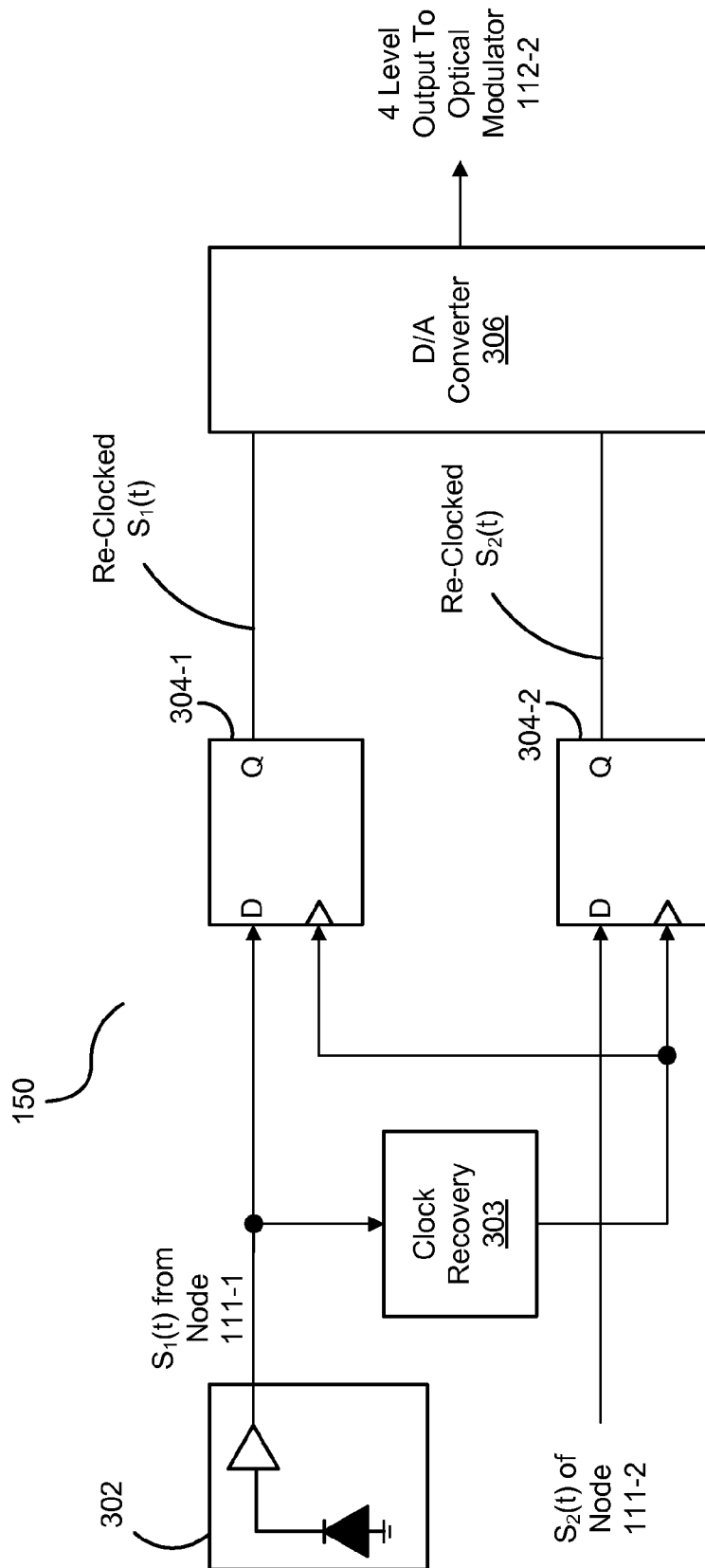


FIG. 12

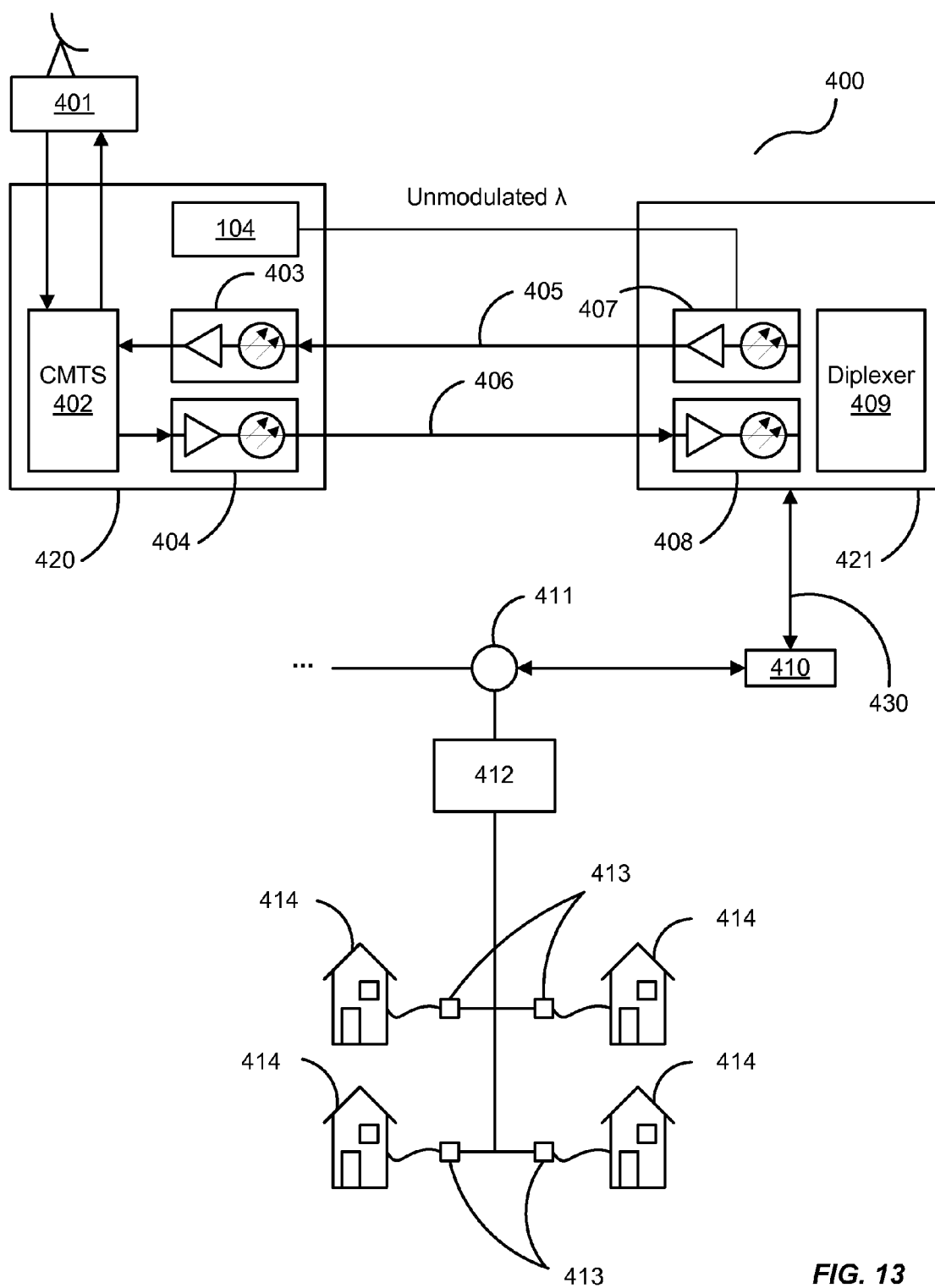


FIG. 13

## OPTICAL COMMUNICATION SYSTEMS AND METHODS

### CROSS REFERENCE TO RELATED APPLICATIONS

This patent application is a non-provisional patent application claiming priority to, and thus the benefit of an earlier filing date from, U.S. Provisional Patent Application No. 61/912,699 (filed Dec. 6, 2013), the entire contents of which are hereby incorporated by reference. This patent application is also related to U.S. patent application Ser. Nos. 14/322,063 and 14/322,078, the entire contents of each of which are also incorporated by reference.

### BACKGROUND

Higher capacity optical links (e.g., 20 GHz to 30 GHz) place greater demands on directly modulated diode lasers. Wavelength division multiplexing provides some relief for these demands. Newer diode lasers are more stable and exhibit narrower linewidths that make coherent optical communications more practical to implement. But, increasing demands for data continue to present problems in optical communications. And, these newer technologies are not always feasible to implement.

### SUMMARY

Systems and methods presented herein provide for optical communications. In one embodiment, a communication system includes an optical link and a communication hub comprising at least two lasers optically coupled to a first end of the optical link, the communication hub further comprising an optical multiplexer operable to multiplex light from the lasers and to propagate the multiplexed light along the optical link. The communication system also includes a communication node comprising an optical modulator optically coupled to a second end of the optical link, wherein the optical modulator is operable to modulate the multiplexed light from the communication hub with one or more modulating signals, and to propagate the modulated light to the communication hub.

The various embodiments disclosed herein may be implemented in a variety of ways as a matter of design choice. For example, some embodiments herein are implemented in hardware whereas other embodiments may include processes that are operable to implement and/or operate the hardware. Other exemplary embodiments, including software and firmware, are described below.

### BRIEF DESCRIPTION OF THE FIGURES

Some embodiments of the present invention are now described, by way of example only, and with reference to the accompanying drawings. The same reference number represents the same element or the same type of element on all drawings.

FIG. 1 is a block diagram of an exemplary optical communication system.

FIG. 2 is a flowchart illustrating an exemplary process of the optical communication system of FIG. 1.

FIG. 3 is a block diagram of an exemplary QAM optical modulator.

FIGS. 4-11 are block diagrams of other exemplary optical communication systems.

FIG. 12 is a block diagram of a synchronization module used in a communication node.

FIG. 13 is a block diagram of an exemplary cable television system employing optical systems and methods herein.

### DETAILED DESCRIPTION OF THE FIGURES

The figures and the following description illustrate specific exemplary embodiments of the invention. It will thus be appreciated that those skilled in the art will be able to devise various arrangements that, although not explicitly described or shown herein, embody the principles of the invention and are included within the scope of the invention. Furthermore, any examples described herein are intended to aid in understanding the principles of the invention and are to be construed as being without limitation to such specifically recited examples and conditions. As a result, the invention is not limited to the specific embodiments or examples described below.

FIG. 1 is a block diagram of an exemplary optical communication system 100. The optical communication system 100 includes a communication hub 101 and a communication node 111. The communication hub 101 and the communication node 111 are optically coupled to one another via a plurality of optical communication links 120 (e.g., a plurality of optical fibers). Although illustrated with a single communication node 111, the communication hub 101 is a center point of communication activity and may be coupled to one or more communication nodes 111 to transmit data to the communication nodes 111. Thus, the communication hub 101 is any system, device, software, or combination thereof operable to optically communicate data to one or more communication nodes 111.

The communication hub 101 comprises an optical transmitter 102 that optically transmits data to the communication node 111 over one or more of the optical links 120. The communication node 111 comprises an optical receiver 103 that is optically coupled to the optical transmitter 102 of the communication hub 101 via the optical links 120. The optical receiver 103 receives optical communications from the optical transmitter 102 of the communication hub 101 and converts the data thereof to electronic data. In this regard, the communication node 111 may transfer the electronic data to one or more receivers 121 (e.g., over radio frequency, RF, via coaxial cable).

The communication node 111 is also operable to optically communicate data to the communication hub 101 over one or more of the optical links 120. In this embodiment, the communication node 111 is configured with an optical modulator 112 that is operable to modulate laser light with a modulating signal source 122. For example, the optical modulator 112 may be communicatively coupled to a coaxial cable conveying an RF signal. The RF signal is propagated to the optical modulator 112 which in turn modulates the laser light. The modulator structure can be configured to amplitude modulate the optical carrier, phase modulate the optical carrier, etc. as desired. In this embodiment, the optical modulator 112 is configured with two coupled phase shifters 114. Also, in this embodiment, the optical modulator 112 is a Mach-Zehnder electro-optical modulator, however, other optical modulators may be used (e.g., acousto-optic modulators, electroabsorption modulators, etc.). Moreover, the modulating signal source 122 may represent other forms of modulating waveforms including digital signals. Thus, with respect to the preceding, the communication node 111 is any system, device, software, or combination thereof operable to optically communicate with a communication hub 111.

To improve the optical integrity of the communication system 100, and more specifically, the optical transmissions



from the communication node **111**, the communication hub **101** is configured with lasers **104-1** and **104-2** that propagate laser light to the optical modulator **112** over one or more of the optical links **120** for return optical communications by the node **111** (e.g., “upstream” communications). For example, diode lasers over time can degrade in terms of performance when they are exposed to harsh conditions where communication nodes **111** may be placed. Thus, the communication hub **101** may incorporate the lasers **104** within an environmentally controlled climate to maintain consistent performance for the laser **104-1** and **104-2**. The lasers **104-1** and **104-2** propagate unmodulated laser light to the optical modulator **112** over the optical communication links **120** such that the communication node **111** can modulate the laser light via the modulating signal source **122** and convey the data thereof to an optical receiver **103** of the communication hub **101**.

The communication hub **101** is also configured with an optical multiplexer **118** that multiplexes laser light from the lasers **104-1** and **104-2** along a common optical link **122** the communication node **111** to increase or otherwise improve capacity of the communication system. For example, if a common optical link **122** is capable of carrying multiple unmodulated light sources to the communication node **111**, multiple streams of data can be modulated at the communication node **111** and propagated back to the communication hub **101** for demodulation.

In this regard, the communication node **111** may also be configured with an optical demultiplexer **119** that demultiplexes the light from lasers **104-1** and **104-2** such that the light may be modulated via the optical modulator **112**. For example, the multiplexer **118** may combine multiple wavelengths of light from the lasers **104** onto a common optical link **120** (e.g., wavelength division multiplexing). The optical demultiplexer **119** may separate those wavelengths of light such that each wavelength may be modulated by its own optical modulator **112** for propagation back to the communication hub **101**.

Alternatively or additionally, the lasers **104** can transmit light at the same wavelength but at different polarizations (e.g., in a polarization division multiplexing scheme). In this regard, the multiplexer **118** may combine the different polarizations of light onto a common optical link **120** where they are separated by the optical demultiplexer **119** in a polarization beam splitting process. For example, the demultiplexer **119** may comprise a polarization beam splitter that separates the polarizations into two or more distinct optical beams such that each polarization may be modulated with its own optical modulator **112** for propagation back to the communication hub **101**.

In yet another embodiment, one or more the lasers **104** may be tunable, such as that found in external cavity lasers (ECL). For example, ECLs are tunable lasers which use double hetero-structure diodes that allow the lasers to operate at different wavelengths. Thus, the multiplexer **118** may multiplex/propagate multiple wavelengths of light in a time division multiplexed fashion based on the frequency at which an ECL switches to other wavelengths. From there, the optical demultiplexer **119** may propagate each time division multiplexed wavelength to its own optical modulator **112** for modulation and propagation back to the communication hub **101**.

Based on the forgoing, the optical multiplexer **118** is any device, system, software, or combination thereof operable to combine light of different wavelengths, polarizations, etc. for propagation to a communication node **111** and modulation by the communication node. And, the optical demultiplexer **119**

is any device, system, software, combination thereof operable to extract multiple beams of light for modulation by the optical modulator **112**.

In some embodiments, the optical demultiplexer **119** may also include a polarization controller. For example, the optical modulator **112** may exhibit polarization sensitivity due to longer optical links **120** that can be marginalized or otherwise reduced through the use of a polarization controller that modifies the polarization of the light to the optical modulator **112** in a desirable fashion. The polarization controller may also be used for the purposes of the aforementioned polarization division multiplexing. For example, a first optical communication signal may be conveyed via light in a particular polarization. To increase the capacity, a second optical communication signal may be conveyed on the same optical link **120** at a polarization that is orthogonal to the first optical communication signal, potentially doubling the capacity.

It should be noted that the communication hub **101**, while illustrated with two lasers **104-1** and **104-2**, the invention is not intended to be limited to the illustrated embodiment. Rather, multiple lasers **104** including those of different types, such as ECLs, may be multiplexed onto a common optical link **120** for propagation to the communication node **111**. And, the various embodiments disclosed herein may be combined in a number of ways as a matter of design choice. Additional details regarding the optical modulator **112** and its various components (e.g., transmission line electrodes, a phase shifter, and a transmitter) are shown and described in FIG. 3. An exemplary operation of the optical communication system **100** is now shown and described the process **200** of FIG. 2.

FIG. 2 is a flowchart illustrating one exemplary process **200** of the optical communication system **100**. In this embodiment, the process **200** initiates when an optical link **120** is established between the communication hub **101** and the communication node **111**. Establishment of the optical link **120** generally includes establishing communications between the communication hub **101** and the communication node **111** over one or more optical fibers run (e.g., buried underground) between the communication hub **101** and the optical modulator **112** of the communication node **111**. For example, the lasers **104** may be coupled to the optical modulator **112** with one of the optical fibers whereas the optical receiver **103** of the communication hub **101** may be coupled to the optical modulator **112** with another of the other optical fibers. But, the concepts described herein may be implemented in other ways as shown and described below.

With the optical link established, the lasers **104-1** and **104-2** propagate light to the optical multiplexer **118** such that the optical multiplexer can multiplex the light at the communication hub **101**, in the process element **201**. The optical multiplexer propagates the multiplexed light along a common optical link **120** to a communication node **111**, in the process element **202**.

The communication node **111** modulates the multiplexed light with one or more modulated signals, in the process element **203**. For example, the communication node may demultiplex the light from the multiplexer **118** depending on the manner in which it was multiplexed as described above. The demultiplexed light is then modulated with one or more optical modulators and propagated to the communication hub **101**, in the process element **204**. The modulated beams of light may be combined in a manner similar to that of the unmodulated light from the communication hub **101** for propagation back to the communication hub **101**. It should be noted that the modulated light from the communication node **111** may be propagated to other intervening communication

nodes **111** along the way to the communication hub **101** and/or even to just the communication nodes **111** themselves. And, each optical modulator **112** may have its own modulating signal source **122**.

The embodiments disclosed herein provide a pathway for higher optical capacities as well as the ability to optimize communications over existing optical links. For example, a traditional cable television node is used to translate amplitude modulated light from a communication hub to an RF signal covering less than 1 GHz of bandwidth. The RF signal is then propagated to households and businesses. The modulation imprinted on an optical carrier can comprise 160 multiplexed digital quadrature amplitude modulation (QAM) or analog National Television System Committee (NTSC) subcarriers. The node has an optical receiver operable to receive signals between about 50 MHz to 1002 MHz. The node also has a laser transmitter intended for upstream return information of about 100 MHz. Increasing demand for data over the limited upstream spectrum has led to the exploration of other upstream ranges of 5 MHz to 85 MHz and 5 MHz to 204 MHz, which generally results in a change to downstream frequency ranges.

NTSC analog signals and other signals can exhibit high linearity and dynamic range. Laser requirements with such parameters are generally very stringent. And, higher signal-to-noise ratios (SNRs) are typically required to support higher order modulations. For example, next generation Data Over Cable Service Interface Specification (DOCSIS) systems, such as DOCSIS 3.1, have been designed to support 4,096 state QAM and 16,384 state QAM. And, the SNR for these modulations generally needs to be significantly higher. It should be noted, however, that NTSC is a United States standard and that the embodiments disclosed herein may also be useful/advantageous with other signaling standards such as those used in the European cable television industry.

Demands on upstream communications from communication nodes (e.g., from cable television data subscribers), such as the communication node **111**, are also pushing cable television operators to use higher quality diode lasers. As upstream communications may encounter many types of interference, SNR is even more important when employing QAM.

One way to increase capacity and alleviate the need for higher SNR and more exotic modulations could be to simply increase the number of optical links between the communication hub of the cable television network (e.g., the communication hub **101**) and the communication node. However, when optical fibers were initially laid to establish the optical links, they were done so in a "loop" configuration in which the communication hub is connected to a plurality of communication nodes cascaded in series with the last communication node in the link connecting back to the communication hub. And, there were only a few fibers dedicated to each node because communication nodes were originally designed to cover 500 to 1000 homes with a fiber bundle connecting these nodes via six to twelve fiber strands. So, increasing the number of optical links to accommodate ever-increasing capacity would mean laying down and burying new bundles of optical fiber, a costly and labor-intensive effort.

Moreover, a node is typically configured in a harsher operating environment than the communication hub. For example, the communication hub typically has sophisticated equipment that needs to be maintained and housed in a stable operating environment. The nodes, however, are typically located in boxes outdoors and have limited space (e.g., due to real estate covenants, property owner rights, etc.). These harsher operating environments eventually degrade perfor-

mance of diode lasers and generally preclude the use of more sophisticated lasers when higher capacity is being sought after. By moving the laser **104** to the more climate controlled environment of the communication hub **101**, laser performance can be extended and even improved. Of course, this is just one example of how the system **100** may be implemented. Other exemplary embodiments are shown and described below.

FIG. 3 is a block diagram of an exemplary QAM optical modulator **112**. In this embodiment, the QAM optical modulator **112** comprises a plurality of "sub-optical modulators" **112-1**, **112-2**, and **112-3**. Each optical modulator **112**, in this embodiment, is configured in a Mach Zehnder architecture. In this regard, each optical modulator **112** includes two coupled phase shifters **114** (e.g., an electrode, a crystal medium, a gain medium, or any combination thereof), a pair of optical waveguides to carry the optical signal in the phase shifters **114**, a pair of transmission line electrodes **113** to modify the effective length of the optical path through electrical stimulation within the coupled phase shifters **114**, and a transmitter **116** operable to convey the signal from the source **122** to the electrodes **113**.

Each optical modulator **112** splits the unmodulated light into its corresponding pair of waveguides **115** around its corresponding coupled phase shifters **114**. As such, the optical waveguides **115** split the unmodulated light into two phase shifted branches and recombine after modulation by the transmitter **116** to form, after the interaction of the two phase shifted branches, an amplitude and phase modulated signal. Along the portion where the optical waveguide **115** splits in two, the electrodes **113** may be configured as transmission lines to achieve relatively high modulation frequencies (e.g., a 100 GHz frequency response).

With this in mind, the optical modulator **112-1** receives unmodulated laser light from the laser **104** along the optical link **120** and modulates the light with a signal from a source **122** via the coupled phase shifters **114-1**. The optical modulator **112-2** also receives the unmodulated laser light from the laser **104** (i.e., at the same wavelength) and modulates that light with a signal from the same or another source **122** via the coupled phase shifters **114-2**. The two phase shift modulated signals from the optical modulators **112-1** and **112-2** are then propagated to the optical modulator **112-3** to combine as a QAM signal via the coupled phase shifters **114-3** and the transmitter **116-3**. For example, the transmitter **116-3** may provide a  $\pi/2$  phase offset that offsets the two signals from the optical modulators **112-1** and **112-2** by 90° from one another to form the Quadrature Phase Shift Keyed (QPSK) signal when the modulators **112-1** and **112-2** generate a 2-level optical signal. By amplitude modulating the input signals to the optical modulators **112-1** and **112-2** beyond 2 levels via the transmitters **116-1** and **116-2**, respectively, the QPSK signal becomes a higher state QAM signal (e.g., 16 state QAM, 64 state QAM) after the 90 degree phase-shift applied by the optical modulator **112-3**.

The optical waveguide pairs **115**, in this embodiment, are illustrated between the electrodes **113**. However, depending on the crystal characteristics of the coupled phase shifters **114**, the transmission line electrodes **113** may be configured above the waveguide pairs **115** within the coupled phase shifters **114**. The coupled phase shifters **114** center electrode **113** is grounded and the top and bottom electrodes **113** typically have equal but opposite sign voltages to achieve equal but opposite sign phase shifts with respect to the same drive voltage.

Generally, Mach Zehnder optical modulator architectures can be manufactured from materials exhibiting certain elec-

tro-optic effects that change the index of refraction based on the voltage applied. As the index of refraction changes, the effective dimension of the optical path changes and a phase shift occurs. Lithium niobate, indium phosphide, and various polymers are some of the materials that may be used to implement the coupled phase shifters **114**. In some embodiments, the phase shifter **114** may be configured with a material that provides an optical gain (e.g., an optical gain medium) to the modulated signal.

Mach Zehnder architectures can be fairly sensitive to polarization changes. Accordingly, the communication system **100** and/or any of the optical modulators **112** involved may be configured with a polarization controller **119** as described above to compensate for a shift in polarization rotation.

The transmitter **116** may be configured in a variety of ways depending on the input signal being used to modulate the unmodulated light from the laser **104**. For example, assuming that the signal from the source **122** is an analog signal (e.g., an RF signal), the transmitter **116** may include an analog to digital converter that converts the analog signal to a digital signal which is thereby used to modulate the unmodulated light via the bipolar stimulation of the electrodes **113**. In another implementation, the digital signal generates a multi-level stimulation that is used to generate an optical QAM signal. In yet another implementation, the transmitter takes the RF source and amplifies it to an optimum level to drive the optical modulator **112** using certain functionality, such as automatic gain control.

Additionally, the signal driving the optical modulator **112** can be conditioned so that it is optimized for high frequency operation. For example, a mismatch can exist between the propagation speed of an electrical signal on electrical transmission lines which connect to the electrodes **113** and the propagation speed through the optical waveguides. The optical signals on the optical waveguide modulated by the electrical signal where the phase shift and/or optical gain of the coupled phase shifters **114** take place can experience distortion. Thus, the electrical signals driving the optical modulator **112** can be conditioned to achieve more linearity (e.g., via pre-distortion conditioning techniques).

As mentioned, the signal driving the optical modulator **112** may be a digital signal that actually improves optical performance. For example, RF signal digitization along increased digital capacity lines can be used to increase transmission performance compared to an analog optical link. To accomplish such, the transmitter **116** may be configured with an analog to digital converter that samples the entire RF signal. In any case, the signal driving circuitry may include delay functionality to allow for other features such as time division multiplexing. A clock input to synchronize re-modulation may be used for implementing other multiplexing techniques. An example of such is illustrated in FIG. **12**.

FIGS. **4-11** are block diagrams of other exemplary optical communication systems. Each of these embodiments may be used to optimize optical communications and increase capacity, more particularly in the upstream optical communications. In FIG. **4**, a communication hub **101** is operable to optically transmit data from an optical transmitter **102** to an optical receiver **103** of a communication node **111**. In this embodiment, the optical data transmitted to the communication node **111** is propagated along an optical link **120** at a wavelength  $\lambda_1$ . The optical receiver **103** of the communication node **111** may then convert the received signal to an analog RF signal conveyed over coaxial cable to a receiver **121**.

The communication hub **101** is also configured with an optical receiver **103** that is similarly used to convert a received signal from an external modulator **112** of the communication node **111**. As with the previous embodiments, the laser **104** is configured with the communication hub **101** to transmit unmodulated light along an optical link **120**. In this embodiment, the laser **104** propagates light at a wavelength  $\lambda_2$  to the external modulator **112** in the communication node **111**. The communication node **111** then modulates the light  $\lambda_2$  at the external modulator **112** in the communication node **111** using the signal from the modulating source **122** (e.g., an RF signal propagated along a coaxial cable).

To assist in reducing the number of optical links **120** used in transmitting data from the communication node **111** to the communication hub **101**, the communication hub **101** also employs an optical circulator **130**. The optical circulator is used to separate optical signals traveling along an optical link **120** in opposite directions. For example, the optical circulator **130** may be a three-port device such that light entering any port exits from the next so as to achieve bi-directional propagation over a single optical link **120**. Thus, the laser **104** can propagate the modulated light at the wavelength  $\lambda_2$  to the external modulator **112** of the communication node **111** for modulation via the modulating source **122** and have the modulated light at the wavelength  $\lambda_2$  propagated along the same optical link **120** to the receiver **103** of the communication hub **101**, thereby reducing the need for an additional optical link **120** as illustrated in the embodiment of FIG. **1**.

The embodiment in FIG. **4** is exemplarily illustrated with the transmitter **102** of the communication hub **101** transmitting light at the light at the wavelength  $\lambda_1$  and the laser **104** transmitting light at the wavelength  $\lambda_2$ . One reason for this leads to the embodiment illustrated in FIG. **5** which allows for yet another optical link **120** to be removed and preserved for other uses such as higher capacity. For example, in FIG. **5**, the communication hub **101** optically transmits optical data from the transmitter **102** at a wavelength  $\lambda_1$ . The laser **104** in the communication hub **101** propagates unmodulated light at a wavelength  $\lambda_2$  to the optical circulator **130** into the communication node **111**. The outbound unmodulated light from the laser **104** is then combined with the optical data at the wavelength  $\lambda_1$  from the external modulator **112** with the optical element **131** (e.g., a diffraction grating or an optical splitter) past the optical circulator **130** to propagate both wavelengths of light along the same optical link **120**.

The combined light of wavelengths  $\lambda_1$  and  $\lambda_2$  arrives at the communication node **111** and are separated by another optical element **131** (e.g., a splitter or diffraction grating). The optical data of the wavelength  $\lambda_1$  from the optical transmitter **102** of the communication hub **101** then propagates to the receiver **103** of the communication node **111**. And, the unmodulated light of the wavelength  $\lambda_2$  propagates to the optical circulator **130** of the communication node **111** where it is modulated by the external modulator **112** with the signal of the modulating source **122**. The modulated light from the external modulator **112** then propagates to the optical circulator **130** so that it can propagate along the same optical link **120** as the unmodulated light (i.e., in the opposite direction). The modulated light is then split by the optical element **131** such that it may be received by the receiver **103** of the communication hub **101** (e.g., after passing through the optical circulator **130**). As can be seen, the different wavelengths being combined on the same optical link **120** allows for another optical link to be freed for other use (e.g., higher capacity).

In FIG. **6**, the communication system **100** propagates the modulated light from the laser **104** at the wavelength  $\lambda_2$

directly to the external modulator **112** of the communication node **111** for modulation. Thereafter, the modulated light from the external modulator **112** of the communication node **111** is combined with the incoming light at the wavelength  $\lambda_1$  from the transmitter **102** of the communication hub **101** at the optical element **131** of the communication node **111** (e.g., again, an optical splitter or a diffraction grating). The modulated light at the wavelength  $\lambda_2$  is then propagated along the same optical link **120** as the incoming light at the wavelength  $\lambda_1$  and is split off from the optical link **120** with the optical element **131** in the communication hub **101** where it is received by the receiver **103**.

FIG. 7 illustrates the communication system **100** with a plurality of cascaded nodes **111-1** and **111-2**. In this embodiment, the communication hub **101** has a receiver **103** for each of the communication nodes **111**. The receiver **103-1** receives upstream communications from the node **111-1** and the receiver **103-2** receives upstream communications from the node **111-2**. The communication hub **101** again comprises a transmitter **102-1** that transmits optical communications at a wavelength  $\lambda_1$  to the node **111-1** and a transmitter **102-2** that transmits optical communications at a wavelength  $\lambda_2$  to the node **111-2**. The communication hub **101** also comprises a laser **104** operable to propagate light at a common unmodulated wavelength  $\lambda_2$  to each of the nodes **111-1** and **111-2**.

As can be seen in this embodiment, the communication hub **101** is optically coupled to the node **111-1** with six optical links **120**. This embodiment is intended to illustrate how an optical network can be configured with a bundle of optical fibers. For example, in a cable television network, the communication hub **101** is connected to a plurality of nodes via a plurality of optical links **120**. Generally, this is implemented with a plurality of optical fibers being laid underground or above ground in a “loop” configuration, with the optical fibers usually being configured in bundles of multiple of six optical fibers. And, each node **111** has its own dedicated optical fiber for upstream communications to the communication hub **101**. Thus, if there are 5 nodes **111** in a loop, then all optical fibers in a bundle of six optical fibers are used because one of the optical fibers is common to each node **111** for downstream communications that uses separate wavelengths and can be aggregated into a single optical fiber coming from the communication hub **101**.

Once laid, the bundle of optical fibers is intended to be a somewhat permanent fixture. Thus, when additional homes connect to a particular node **111** and/or when additional capacity is required of a node **111**, communications over the fixed number of optical fibers is at a premium.

This embodiment and others below alleviate some of the problems associated with fixed bundles of optical fibers. In this embodiment, the node **111-1** is optically coupled to the communication hub **101** via six optical links **120**, four of which are shown as being unused because only two nodes **111** are illustrated. The communication hub **101** transmits communications to each of the nodes **111-1** and **111-2** along a common optical link **120** respectively at the wavelengths  $\lambda_1$  and  $\lambda_2$ . The communication hub **101** propagates unmodulated light at the wavelength  $\lambda_2$  along another common optical link **120**. The node **111-1** modulates the light at the wavelength  $\lambda_2$  via its modulating source **122** (not shown) and propagates the modulated light to the node **111-2** along yet another of the optical links **120**. The node **111-1** also propagates the unmodulated light at the wavelength  $\lambda_2$  to the node **111-2** along an unused fiber so that it can modulate it via its modulating source **122** (not shown) and propagate its upstream communications to the communication hub **101**.

The node **111-2**, being the last node in the loop before the communication hub **101**, can simply modulate the light at the wavelength  $\lambda_2$  and propagate it along the same optical link used to carry the unmodulated light at the wavelength  $\lambda_2$  to the node **111-2**. Thus, four optical links **120** remain unused from the node **111-2** to the communication hub **101**, meaning there are 4 additional optical links **120** that could be used for additional capacity.

It should be understood that, while the communication system **100** in this embodiment is illustrated with two nodes **111-1** and **111-2**, the invention is not intended be limited to the illustrated embodiment. The communication system **100** can be and typically is configured with more nodes **111** than illustrated in this embodiment.

FIG. 8 illustrates an embodiment in which the communication hub **101** comprises a plurality of lasers **104-1-104-N** (where the reference “N” is merely intended to represent an integer greater than one and not necessarily equal to any other “N” reference used herein), each operating at a particular wavelength  $\lambda$  (i.e.,  $\lambda_{N+1}-\lambda_{2N}$ ). The lasers **104-1-104-N** are, like in previous embodiments, operable to propagate unmodulated light to a communication node **111** such that the communication node **111** can modulate the light and propagate it back to the communication hub **101**. The communication hub **101** may selectively couple one or more of the lasers **104-1-104-N** to the communication node **111** over the plurality of optical links **120**.

The communication hub **101**, in this embodiment, includes a temperature/climate controlled environment that allows the lasers **104-1-104-N** to operate with stable output characteristics. This implementation combines configuration flexibility with certain performance improvements. For example, the lasers **104-1-104-N**, being external cavity lasers, may be selected based on the size of the external cavity. In other words, the wavelength necessary to maintain coherent communications with the desired separation in frequency or wavelength may depend on the cavity length. Accordingly, the controller **140** may select a particular laser wavelength for any given node. And, since they are separate wavelengths, the light from lasers **104-1-104-N** can be propagated along a common optical link **120**.

Turning now to FIG. 9, the communication system **100** in this embodiment provides wavelength multiplexing over the optical links **120** to a plurality of cascaded nodes **111** (e.g., nodes **111-1** and **111-2**). In this embodiment, the communication hub **101** transmits downstream data at a wavelength  $\lambda_1$  and the laser **104** propagates unmodulated light at a wavelength  $\lambda_2$ . The two wavelengths of light are combined (i.e., multiplexed) at the optical element **131** and propagated to the node **111-1** over a single optical link **120**.

The other optical link **120** between the communication hub **101** and the node **111-1** is again illustrated in this embodiment as being unused for the purposes of showing how installed fiber optic links can be optimized for capacity. As mentioned, the number of optical links **120** may be at a premium. This is particularly true with the trend of “shrinking” node sizes due to capacity increases. For example, in a cable television network, a node **111** may communicatively couple to a plurality of households and businesses via RF over a coaxial cable. As communication capacity demands increase for each of the household and businesses, the node **111** may have less ability to serve those capacity demands. Accordingly, the node **111** shrinks to serve fewer households and businesses and another node **111** is established for those households and businesses removed or otherwise “squeezed out” of the previous node **111**.

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Wavelength division multiplexing has been used and will likely continue to be used to alleviate problems associated with fewer optical links due to shrinking node sizes. But, when data rates increase (e.g., 40 Gigabits per second, or Gbps), wavelengths come at a premium. For example, multiple wavelengths  $\lambda$  of light can be propagated along the single optical link **120**. When each wavelength  $\lambda$  of light is used to transmit more capacity, the spectrum used by the transmitter of the wavelengths  $\lambda$  of light are widened. Eventually, the optical link simply runs out of spectrum to transmit, thus requiring more of the fixed number of optical links **120**. In other words, more capacity eventually translates into a higher number of optical links needed which may be impractical when the optical links are already established and buried underground.

There are different ways of multiplexing signals of different nodes **111**. For example, multiplexing can be performed solely in the digital optical domain through coordinated optical re-modulation in a subsequent node **111**. Alternatively, multiplexing may be performed in the electrical domain by detecting, multiplexing data streams, and then modulating the aggregate data stream.

In the digital optical domain, basic modulation of light takes place by changing characteristics of the light (e.g., such as frequency, phase, intensity, etc.). For example, by changing the intensity of a laser between two states, one can provide an amplitude modulated digital signal. By employing more exotic and complex modulation schemes such as QAM, each symbol in the modulation scheme represents multiple bits and therefore can be used to increase capacity in terms of the overall data rate, but at the expense of greater complexity.

In this embodiment, the unmodulated light at the wavelength  $\lambda_2$  from the laser **104** is split off by the node **111-1** from the communications of the transmitter **102** in the communication hub **101** (i.e., the wavelength  $\lambda_2$  of light). The node **111-1** then modulates the light at the wavelength  $\lambda_2$  via its respective modulating source **122** (not shown) and propagates both the downstream communications and the modulated light at the wavelength  $\lambda_2$  along the same optical link to the node **111-2**. The node **111-2** then splits off the downstream communications from the communication hub **101** and “re-modulates” the light at the wavelength  $\lambda_2$  modulated by the node **111-1** using its respective modulating source **122** (not shown). The node **111-2** then propagates the light at the wavelength  $\lambda_2$  modulated by both nodes **111-1** and **111-2** and conveys their respective upstream communications to the receiver **102** of the communication hub **101** over the same optical link **120** and carrier wavelength  $\lambda_2$ .

Such may be implemented using QAM modulation. An optical delay **140** prior to the modulator **112** of the node **111-2** may be used to provide the node **111-1** with sufficient timing for synchronization purposes. Through the use of coherent optical links **120**, this multiplexing scheme can be expanded to more nodes. Thus, the modulation technique may increase with the number of nodes. For example, four nodes **111-1** to **111-4** each applying a bi-level (2-level) modulation through proper modulation mechanisms may result in a combined 16 state QAM signal being propagated from the node **111-4** to the communication hub **101**. Further modulation techniques are shown and described in FIGS. **10** and **11**.

FIG. **10** is a block diagram of the modulators **112-1** and **112-2** of the nodes **111-1** and **111-2**, respectively. The downstream communications from the communication hub **101** are not shown in this embodiment for the sake of simplicity. Rather, this embodiment only illustrates the modulators **112** so as to show one exemplary implementation of the unmodulated wavelength of light  $\lambda_2$  that gets modulated by the two

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nodes **111-1** and **111-2**. Again, it should be noted that the invention is not intended to be limited to any particular number of nodes or their particular configurations as the embodiments herein may be combined in various ways as a matter of design choice.

In this embodiment, the modulator **112-1** of the node **111-1**, being the first node in the cascaded optical loop, receives unmodulated light at the wavelength  $\lambda_2$  at the gain medium **114** of the modulator **112-1**. The modulator **112-1** modulates that light with its respective modulating source **122-1** (e.g., an RF signal conveyed over coaxial cable) via its transmitter **116**. That modulated light at the wavelength  $\lambda_2$  is then propagated to the optical delay **140** to synchronize the light for modulation by the modulator **112-2** of the node **111-2**. The optical delay **140** may be configured with the optical element **131** (e.g., a splitter or a diffraction grating) and an optical delay element **142** (e.g., an optical cavity of mirrors such as that found in a Herriott delay line). The optical element **131** splits off a portion of the modulated light at the wavelength  $\lambda_2$  which is propagated to a synchronization module **150**. The remaining portion of the modulated light at the wavelength  $\lambda_2$  is propagated to the gain medium **114** of the modulator **112-2**.

The synchronization module **150**, detects the split-off optical signal ahead of time from the same optical signal arriving directly at the modulator. The synchronization module **150** uses that detected signal from the modulator **112-1** to synchronize and condition the modulation signal from modulating source **122-2**. The newly synchronized conditioned electrical modulation signal is then transferred to the transmitter **116** of the modulator **112-2** such that the upstream communications of the node **111-2** can be modulated onto that light at the precise time and at the right amplitude, thereby re-modulating light from the modulator **112-1**. From there, the twice modulated light is propagated at the carrier wavelength  $\lambda_2$  to convey the upstream communications from the both of nodes **111-1** and **111-2** to the communication hub **101**.

FIG. **11** is a block diagram of the modulators **112-1** and **112-2** of the nodes **111-1** and **111-2**, respectively, in another exemplary implementation of cascaded nodes for upstream optical communications. In this embodiment, the unmodulated light at the wavelength  $\lambda_2$  is split (e.g., via an optical element **131**) before reaching the modulators **112-1** and **112-2**. Thus, each modulator **112** directly receives the unmodulated light which is propagated to their respective gain mediums **114**. The node **111-1** modulates the light at the wavelength  $\lambda_2$  via its modulating source **122-1** and propagates it to the synchronization module **150** of the node **111-2**. The synchronization module **150** then detect the light, synchronizes the generated electrical signal from the node **111-1** with its modulating source **122-2** and transfers the synchronized/modulated electrical signal to the transmitter **116** of the modulator **111-2** for modulation of the unmodulated light directed to the coupled phase shifters **114** of the modulator **112-2**. The optical signal with the combined modulation of carrier wavelength  $\lambda_2$  is then propagated to the communication hub **101** to convey the upstream communications of both nodes **111-1** and **111-2**.

The synchronization module **150**, at least in this embodiment, does not add latency due to processing or decoding of the signal. Rather, the synchronization module **150** detects the modulated light from the modulator **112-1** to recover clock and use the clock as the basis for synchronization to aggregate the data streams from the nodes **111-1** and **111-2** so that symbol transitions of the two streams are aligned. One exemplary embodiment of the synchronization module **150** is illustrated in FIG. **12**.

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In FIG. 12, the synchronization module 150 comprises an optical to electrical converter 302 that converts the modulated light at the wavelength  $\lambda_2$  from the node 111-1 to an analog signal  $s_1(t)$ . The clock of the analog signal  $s_1(t)$  is then recovered by the clock recovery module 303 and transferred to the D flip-flop 304-2 such that the analog signal  $s_2(t)$  can be gated with the analog signal  $s_1(t)$  via the D flip-flop 304-1. The re-clocked analog signals  $s_1(t)$  and  $s_2(t)$  are then converted to digital signals by the D/A (digital to analog) converter 306 as a four level output to the optical modulator 112-2. This four level digital output is then transferred to the transmitter 116 of the modulator 112-2 so as to QAM modulator the unmodulated light at the wavelength  $\lambda_2$  propagated to the coupled phase shifters 114 of the modulator 112-2.

FIG. 13 is a block diagram of an exemplary communication system 500 employing the optical communication concepts described herein. For example, the optical communication concepts disclosed herein may be implemented in a cable television communication system that employs RF signaling techniques across a substantial amount of RF spectrum. An upstream link of the cable television communication system, in this embodiment, provides high speed data services being delivered over devices conforming to the Data Over Cable Service Interface Specification (DOCSIS) specification. The communication system 400 includes a headend 401 configured with a communication hub 420. The hub 420 is coupled to a node 421 via optical communication links 405 and 406.

The hub 420 includes a Cable Modem Termination System (CMTS) 402, an electrical to optical converter 403, and an optical to electrical converter 404. The node 421 is similarly configured with an optical to electrical converter 408 and an electrical to optical converter 407. The analog to digital (A/D) conversion is generally performed by the electrical to optical converters 403 and 407.

The headend 401 is generally the source for various television signals. Antennas may receive television signals that are converted as necessary and transmitted over fiber optic cables 406 to the node 421 by the hub 420. Several hubs may be connected to a single headend 401 and the hub 420 may be connected to several nodes 421 by fiber optic cable links 405 and 406. The CMTS 402 may be configured in the headend 401 or in the hub 420. The fiber optic links 405 and 406 may be driven by diode lasers, Fabry Perot lasers, distributed feedback (DFB) lasers, as a few examples.

Downstream, in homes/businesses are devices called the Cable Modems (CM; not shown). A CM acts as a host for an Internet Protocol (IP) device such as personal computer. Transmissions from the CMTS 402 to the CM are carried over the downstream portion of the cable television communication system generally from 54 to 860 MHz. Downstream digital transmissions are continuous and are typically monitored by many CMs. Upstream transmissions from the CMs to the CMTS 402 are typically carried in the 5-42 MHz frequency band, the upstream bandwidth being shared by the CMs that are on-line. However, with greater demands for data, additional frequency bands and bandwidths are continuously being considered and tested, including those frequency bands used in the downstream paths.

The CMTS 402 connects the local CM network to the Internet backbone. The CMTS 402 connects to the downstream path through the electrical to optical converter 404 that is connected to the fiber optic cable 406, which in turn, is connected to the optical to electrical converter 408 at the node 421. The signal is transmitted to a diplexer 409 that combines the upstream and downstream signals onto a single cable. The diplexer 409 allows the different frequency bands to be combined onto the same cable. The downstream channel width in

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the United States is generally 6 megahertz with the downstream signals being transmitted in the 54 to 860 MHz band. Upstream signals are presently transmitted between 5 and 42 MHz, but again other larger bands are being considered to provide increased capacity. The various optical modulation concepts herein may be particularly advantageous. However, the invention is not intended to be limited to any particular form of communication system.

After the downstream signal leaves the node 421, the signal is typically carried by a coaxial cable 430. At various stages, a power inserter 410 may be used to power the coaxial line equipment, such as amplifiers or other equipment. The signal may be split with a splitter 411 to branch the signal. Further, at various locations, bi-directional amplifiers 412 may boost and even split the signal. Taps 413 along branches provide connections to subscriber's homes 414 and businesses.

Upstream transmissions from subscribers to the hub 420/headend 401 occur by passing through the same coaxial cable 430 as the downstream signals, in the opposite direction on a different frequency band. The upstream signals are sent typically utilizing Quadrature Amplitude Modulation (QAM) with forward error correction. The upstream signals can employ any level of QAM, such as 8 QAM, 32 QAM, 64 QAM, 128 QAM, 256 QAM, 4,096 QAM and 16,384 QAM. Of course, other modulation techniques such as Synchronous Code Division Multiple Access (S-CDMA) and Orthogonal Frequency Division Multiple Access (OFDMA) can be used, as desired.

Transmissions, in this embodiment, are typically sent in accordance with the DOCSIS standards. The diplexer 409 splits the lower frequency signals from the higher frequency signals so that the lower frequency, upstream signals can be applied to the electrical to optical converter 407 in the upstream path. The electrical to optical converter 407 converts the upstream electrical signals to light waves which are sent through fiber optic cable 405 and received by optical to electrical converter 403 in the node 420.

Although generally described with respect to the communication hub 101 being "upstream" and the communication node 111 being "downstream", these terms are merely intended to be exemplary. Nor is the invention intended to be limited to cable television systems for any number of wavelengths, nodes 111, optical links 120, etc. Rather, the inventive concepts shown and described herein are merely intended to illustrate how optical communications between two components in a communication system can be optimized or otherwise improved. In this regard, the inventive concepts shown and described herein provide certain advantages over traditional optical communications. One advantage includes the signal generation and optical modulation functions being decoupled from one another. External modulators can then handle higher optical power levels leading to a high dynamic range and reduced non-linear distortion.

For example, direct modulation of diode lasers at higher frequencies is generally achieved at the expense of optical power, making data transmissions beyond 20 GHz exceptionally difficult. External modulation means that less optical power can be used and higher data transmissions can be more easily attained. And, decoupling the optical transmitter from the modulator allows one to focus optical efforts on other performance parameters including higher power, higher frequency response, narrower linewidth for better optical coherence, etc. Moreover, the external modulator can be configured to work as both an intensity modulator and as a coherent QAM modulator depending how it is driven, as shown and described above.

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Another advantage of these embodiments regards the use of more sophisticated lasers. For example, analog fiber optic links can convey analog RF signals by amplitude modulating light from a diode laser. Used in cable television networks, these signals generally have optimal SNRs that approach 50 dB. However, as capacity requirements in cable television increase, the SNR of analog fiber optic has become the bottleneck in achieving higher efficiency systems because the diode lasers cannot effectively convey the larger bandwidth RF signals of the higher capacities. Thus, cable television networks seek to digitize RF signals, which uses even more bandwidth but at a lower cost because digital processing capabilities have increased substantially.

To do so, higher order QAM modulations can be used to represent many bits per symbol and digitize the entire RF spectrum available to the cable television network. This generally means that more exotic/higher power lasers are used. One such laser the DFB laser. A DFB laser is a type of diode laser, quantum cascade laser, or optical fiber laser where an active region of the device is periodically structured as a diffraction grating. The structure builds a one-dimensional interference grating (Bragg scattering) and the grating provides optical feedback for the laser. These lasers provide much faster data rates (e.g., 10 Gigabits) but they are also temperature dependent. Altering the temperature of the DFB laser causes a pitch of the grating to change due to the refractive index dependence on temperature. So, the DFB laser should be placed in a climate controlled environment such as the communication hub **101** to allow the optical communication system **100** to achieve higher optical power and/or higher capacity.

Another such laser is an external cavity laser. The external cavity laser has a narrower linewidth than DFB lasers and is suitable for coherent communications which result in higher efficiency use of bandwidth due to multiple bits per symbol.

In some embodiments, optical amplifiers such as an erbium doped fiber amplifiers may be used to provide optical amplification over an amplification medium that takes place outside the modulator to compensate for losses in the network due to fiber attenuation. Alternatively or additionally, optical amplifiers may be employed anyplace where light is split to provide additional amplification. And, although the term laser is used herein, other optical sources may be used. Generally, any optical source with narrower linewidths could be used in lieu of the laser **104**.

What is claimed is:

**1.** A communication system, comprising:  
an optical fiber;

a communication hub comprising an optical circulator coupled to a first end of an optical fiber, an optical receiver coupled to the first end of the optical fiber via the optical circulator, and a laser coupled to the first end of the optical fiber via the optical circulator, wherein the optical circulator is operable to separate optical signals traveling in opposite directions along the optical fiber by directing incoming optical signals to the optical receiver and directing outgoing unmodulated light from the laser to a second end of the optical fiber;

a communication node comprising an optical modulator optically coupled to the second end of the optical fiber, wherein the optical modulator is operable to modulate the unmodulated light, received from the laser of the communication hub, with one or more modulating signals, and to propagate the modulated light to the communication hub, wherein the communication node further comprises an optical circulator that is coupled to the

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second end of the optical fiber and is operable to separate optical signals traveling in opposite directions along the optical fiber; and

a multiplexer operable to multiplex the outgoing unmodulated light with outgoing modulated light from the communication hub, wherein the multiplexer is located between the optical circulator of the communication hub and the optical circulator of the communication node.

**2.** The communication system of claim **1**, wherein: the one or more modulating signals are Radio Frequency signals propagated from a coaxial cable.

**3.** The communication system of claim **1**, wherein: the optical circulators comprise three-port optical circulators.

**4.** The communication system of claim **3**, wherein: the communication hub further comprises a beam-splitting polarizer operable to separate outgoing unmodulated light from each of multiple lasers at the communication hub,

wherein the optical modulator is further operable to modulate each polarization of light with one of the one or more modulating signals.

**5.** The communication system of claim **1**, wherein: the communication hub further comprises multiple lasers that each generate outgoing unmodulated light at a different wavelength.

**6.** The communication system of claim **5**, wherein: the optical modulator is further operable to modulate each wavelength of light with one of the one or more modulating signals.

**7.** The communication system of claim **1**, wherein: the laser is tunable to lase at different wavelengths of light.

**8.** The communication system of claim **7**, wherein: the tunable laser is an external cavity laser.

**9.** The communication system of claim **7**, wherein: the communication hub further comprises a multiplexer operable to time division multiplex the different wavelengths of light from the tunable laser and to propagate the multiplexed light of the tunable laser to the communication node.

**10.** The communication system of claim **1**, wherein: the optical modulator comprises one or more phase shifters operable to modulate light from the laser with the one or more modulating signals.

**11.** The communication system of claim **1**, wherein: the optical modulator is a Mach-Zehnder optical modulator.

**12.** The communication system of claim **1**, wherein: the communication hub is a cable television headend; and the communication node is operable to provide cable television signals from the headend to a plurality of taps.

**13.** A method, comprising:  
operating a laser to generate unmodulated light at a communication hub for transmission from a first end of an optical fiber via an optical circulator of the communication hub;

multiplexing the outgoing unmodulated light with outgoing modulated light from the communication hub, at a multiplexer that is located between the optical circulator of the communication hub and an optical circulator of the communication node;

receiving the unmodulated light at a communication node at a second end of the optical fiber;

modulating the unmodulated light at the communication node with one or more modulating signals;

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transmitting the modulated light to the communication hub; and  
operating the optical circulator of the communication node to separate optical signals traveling in opposite directions along the optical fiber.

**14.** The method of claim **13**, further comprising:  
multiplexing light from each of at least two lasers at the communication hub in a corresponding number of polarizations.

**15.** The method of claim **14**, further comprising:  
separating light from each of multiple lasers at the communication hub with a beam-splitting polarizer; and  
modulating each polarization of light with one of the one or more modulating signals.

**16.** The method of claim **13**, wherein:  
wavelengths of light from each of multiple lasers at the hub are different; and  
the method further comprises multiplexing the different wavelengths of light to propagate along a common optical fiber.

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**17.** The method of claim **16**, further comprising:  
modulating each wavelength of light with one of the one or more modulating signals.

**18.** The method of claim **13**, further comprising:  
tuning at least one of multiple lasers at the communication hub to lase at different wavelengths of light;  
time division multiplexing the different wavelengths of light from the tunable laser; and  
propagating the multiplexed light of the tunable laser to the communication node.

**19.** The method of claim **13**, wherein:  
modulating the unmodulated light comprises modulating multiplexed light with a Mach-Zehnder optical modulator.

**20.** The method of claim **13**, wherein:  
the communication hub is a cable television headend;  
the communication node is operable to provide cable television signals from the headend to a plurality of taps; and  
the one or more modulating signals are Radio Frequency signals propagated from a coaxial cable.

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